

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

NGR-48-002-00

INTERDISCIPLINARY RESEARCH AND DEVELOPMENT ON
THE EFFECTS OF THE NATURE AND PROPERTIES OF CERAMIC MATERIALS
IN THE DESIGN OF ADVANCED STRUCTURAL COMPONENTS

(NASA-CR-155733) INTERDISCIPLINARY RESEARCH N78-17223
AND DEVELOPMENT ON THE EFFECTS OF THE NATURE
AND PROPERTIES OF CERAMIC MATERIALS IN THE HC A03/MF 401
DESIGN OF ADVANCED STRUCTURAL COMPONENTS Unclas
Semiannual Status Report (Washington Univ.) G3/27 05430

Semi-Annual Status Report Number 29

January 16, 1978



University of Washington

College of Engineering

Seattle, Washington 98195

SUMMARY

A major redirection of research supported by the National Aeronautic and Space Administration on ceramic materials resulted in the establishment of an educational development and supportive research program at the University of Washington. The principal goal of the program is to advance design methodology, to improve materials and to develop engineers knowledgeable in design with and use of high performance ceramic materials.

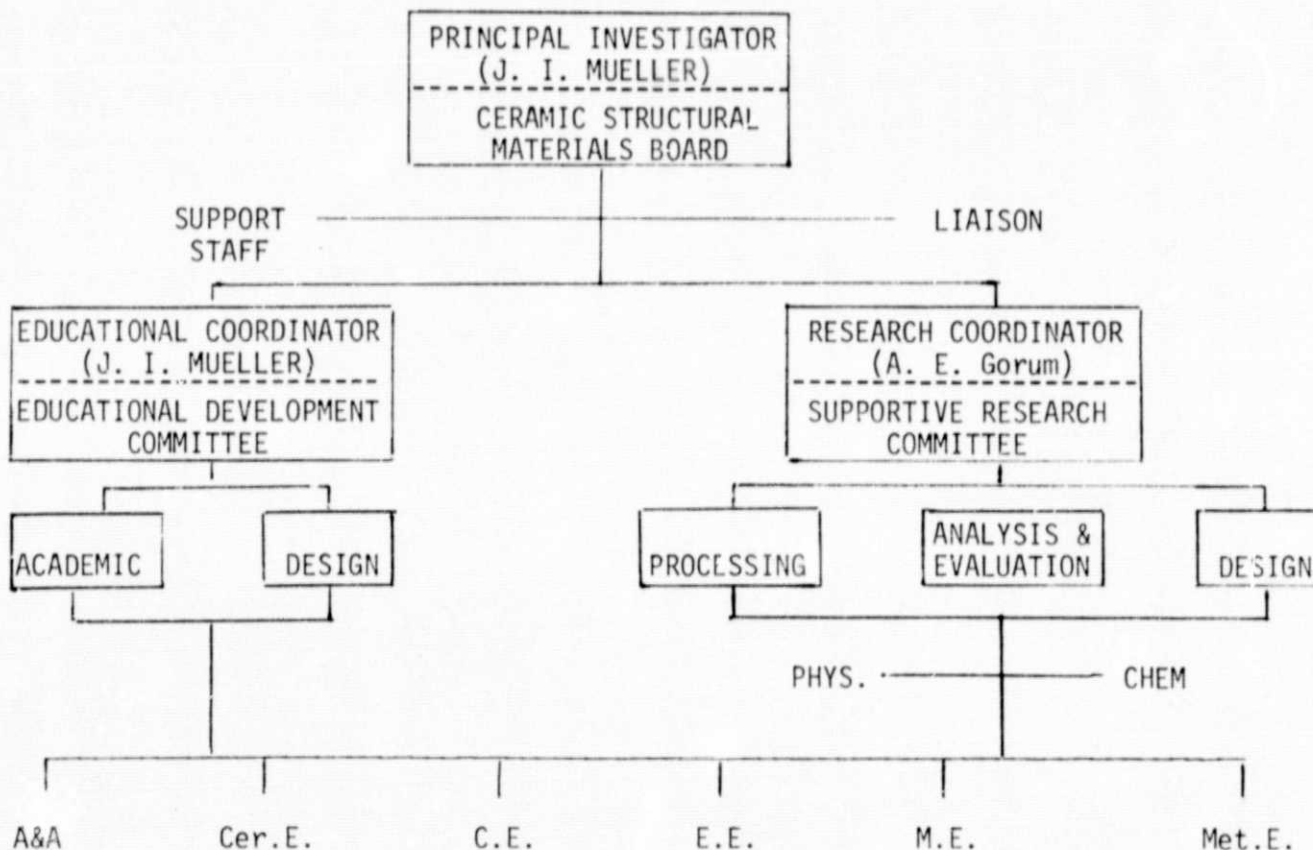
Planning is continuing but implementation of the academic development and supportive research began during this report period. Communications with appropriate industrial organizations and government agencies have been established and are continuing to assure future mutual support and assistance. The previous IDL research is in its terminal phase and will be completed within the current year.

INTRODUCTION

The redirection of the interdisciplinary research program on ceramic materials last year resulted in a new program involving educational development and supportive research on structural design with ceramic materials in high technology. The IDL projects are being phased out this year but both are supported by NASA grant number NSG 48-002-004. Aspects of each program will be discussed in this report. Planning and organization were the major features of the first year of the educational development and supportive research effort, and both areas became operational during the current report period.

Dr. Suren Sarian resigned in June 1977, a regrettable loss since his efforts were significantly responsible for the success of the solid electrolyte projects in the IDL program. His position has been filled by Dr. Alvin E. Gorum, formerly Director of the Army Materials and Mechanics Research Center, who will coordinate the research portion of the new program.

Administrative responsibility for this program remains vested to the Dean of the College of Engineering, who appoints a board of faculty members to establish policy and approve the general operations. In order to assure proper coordination to appropriate interdisciplinary cooperation, the program has been organized according to the following chart.



At present, the Ceramic Structural Materials Board consists of the following:

J. I. Mueller, Ceramic Engineering, Principal Investigator and Chairman
B. W. Mar, Civil Engineering, Associate Dean of Engineering for Research
J. G. Dash, Physics, representing the Dean of the College of Arts and Sciences (on leave)
D. G. Dow, Electrical Engineering
A. S. Kobayashi, Mechanical Engineering
W. D. Scott, Ceramic Engineering
T. G. Stoebe, Metallurgical Engineering

The membership of each of the coordinating committees is given in the appropriate section of this report.

EDUCATIONAL DEVELOPMENT

Coordinating Committee

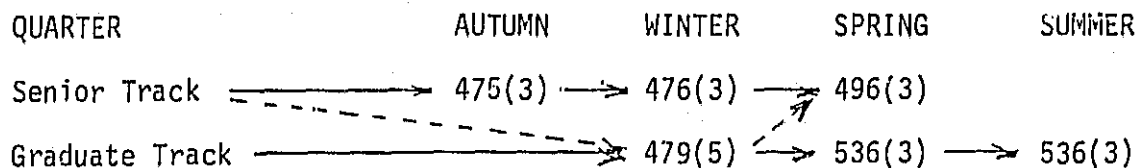
J. I. Mueller, Ceramic Engineering, Chairman
 R. J. H. Bollard, Aeronautics & Astronautics
 B. J. Hartz, Civil Engineering
 A. S. Kobayashi, Mechanical Engineering
 W. J. Love, Mechanical Engineering
 A. D. Miller, Ceramic Engineering
 W. D. Scott, Ceramic Engineering
 R. Taggart, Mechanical Engineering
 O. J. Whittemore, Ceramic Engineering

Objectives for 1977-78

1. Initiate the academic development program, including the design problem sequences.
2. Prepare and distribute information on this and other campuses in order to secure additional student interest in the program.
3. Complete the first-phase processing and testing facility to support both the educational development and research areas.
4. Introduce appropriate subject matter regarding brittle (ceramic) materials in departmental third-year courses.
5. Develop a plan for industrial cooperation.

Progress

A series of experimental courses for the academic portion of this program were outlined and approval has been obtained at all levels of the University. A two-track plan has been established, one for students at each of the undergraduate and graduate levels. Both tracks include academic and design courses and all courses have the designation of each participating department, viz, Ceramic Engineering, Mechanical Engineering, etc. The following diagram indicates the sequences of courses in each track with the number of credit hours listed parenthetically:



The dotted line indicates that some exceptional seniors would have the option of enrolling in 479, with permission, then continuing with the senior design problem.

ORIGINAL PAGE IS
OF POOR QUALITY

Academic Courses

Approval of these courses was not obtained until late in May of 1977 which precluded the 475-476 series being offered this year since they could not be included in the autumn quarter time schedule for advance registration. It was proposed to offer a special 15-credit course in ceramic engineering during summer quarter for non-major students but instead it was deemed advisable to offer 479 on a trial basis to a select group of advanced M.S. students with an interdisciplinary mix. This was accomplished with more than a little success. The class included two students in ceramic engineering, two in civil engineering and one mechanical engineering student. The course is nominally scheduled for three one-hour lecture periods, one two-hour quiz period and one three-hour laboratory period per week. For this trial, the quiz periods were utilized for lecture presentations making a total of 5 hours per week. This change was made in order that each faculty member would be assured sufficient time to present his subject recognizing that redundancy would result and be eliminated after the fact. The sequence of topics was as follows:

Subject	Instructor	Number of Periods	
		Lecture	Lab
Introduction	Mueller	1	--
Ceramic Materials	Miller	3	1
Processing	Whittemore	5	2
Microstructure	Scott	3	2
Continuum Mechanics	Bollard	7	1
Strength and Failure	Hartz	7	1
Fracture Mechanics	Kobayashi	5	1
Non-Destructive Evaluation	Campbell	1	--
Weibull Statistics	Scott	1	--
Design	Taggart	10	2
Critique	Mueller	1	--
		<hr/> 44	<hr/> 10

Each participating faculty member prepared a 20-30 page draft of the material to be covered and copies of these were distributed to student and faculty. The presence of the instructors during the class meetings resulted in an excellent interdisciplinary discussion among both the students and faculty.

A critique was held at the conclusion of the course and some of the comments will be found in Appendix I.

Based upon this review, several decisions were made.

(1) The course should be revised using a scenario approach. The initial periods would be devoted to methods and requirement for the design of a gas turbine utilizing present technology. Subsequently the advantages and limitations of higher inlet temperatures would be discussed and the nature of properties of ceramic materials would be introduced. Periods following this would be devoted to failure mechanisms, structural evaluation of test data and the application of these in the design of a turbine rotor.

(2) This course, as revised, should be offered in Winter Quarter, 1978 with all faculty again in attendance.

(3) The senior design course should be prepared and offered during Spring Quarter with a possible one quarter follow-on of the graduate design course.

All of these are being implemented for Winter and Spring Quarters 1978. In addition, improvements have been made as the working notes which will be available to students enrolled in these courses. They are to be considered as drafts, however, and not to be available for general distribution until additional editing has been accomplished.

Design Projects

It had been previously determined that the design projects should meet the following criteria:

1. The problem should be relevant and meaningful.
2. The problem should have both mechanical and thermal aspects which require special design consideration.
3. The material to be utilized and facilities for fabrication of test specimens and components should be available.
4. The final component should be tested.

In addition, a consensus agreed that a spinning disc offered the optimum immediate promise. Planning for the senior design project was initiated during the report period with details to be considered and developed during the next three months. It is anticipated that two materials iterations and one design iteration can be included within the existing time constraints. This will probably require our obtaining commercially available specimens to be used as the second and third materials.

Facilities and Equipment

The University's facilities planning organization has approved funding for the renovations of approximately 2600 square feet of space in the basement of Roberts Hall to be dedicated for use in this program. This space is currently used by the departmental machine shop and additional space must be prepared for it and the shop moved to this new location. Funds for this have also been approved and plans for both projects are currently being prepared. It is contemplated that the first portion of the new program area should be ready for occupancy within the first month of winter quarter, the remainder by the end of spring quarter.

A furnace capable of 1650°C in vacuum or 1482°C in a nitriding atmosphere has been purchased and received. Manufactured by Richard D. Brew and Company, according to plans developed jointly with Garrett-Airesearch, Inc., the furnace is equipped with a sophisticated programable control system and is to be utilized in reaction sintering of silicon nitride. The furnace should be installed and operating within 60 days.

A table model Instron unit was purchased and has been delivered. This, together with another Instron unit with a high temperature capability will be installed in the dedicated area when it becomes available. Additional processing, testing and finishing equipment will be added as space and funding become available. These facilities and equipment will be utilized in both the academic and supportive research areas.

SUPPORTIVE RESEARCH

Coordinating Committee

A. E. Gorum, Ceramic Engineering, Chairman
A. F. Emery, Mechanical Engineering
J. L. Bjorkstam, Electrical Engineering
W. D. Scott, Ceramic Engineering
R. G. Stang, Metallurgical Engineering

Objectives

The goal of the research portion of this program is to keep abreast of the overall program in high performance structural ceramics in this country and elsewhere, and to do research in those areas that are deemed most appropriate whether it be related to materials or to structures. This should result in the University of Washington being a central focus for information and research in the area of high performance ceramics. The objective for the current year is to initiate a meaningful effort and to develop additional interest among the University faculty in research areas deemed appropriate.

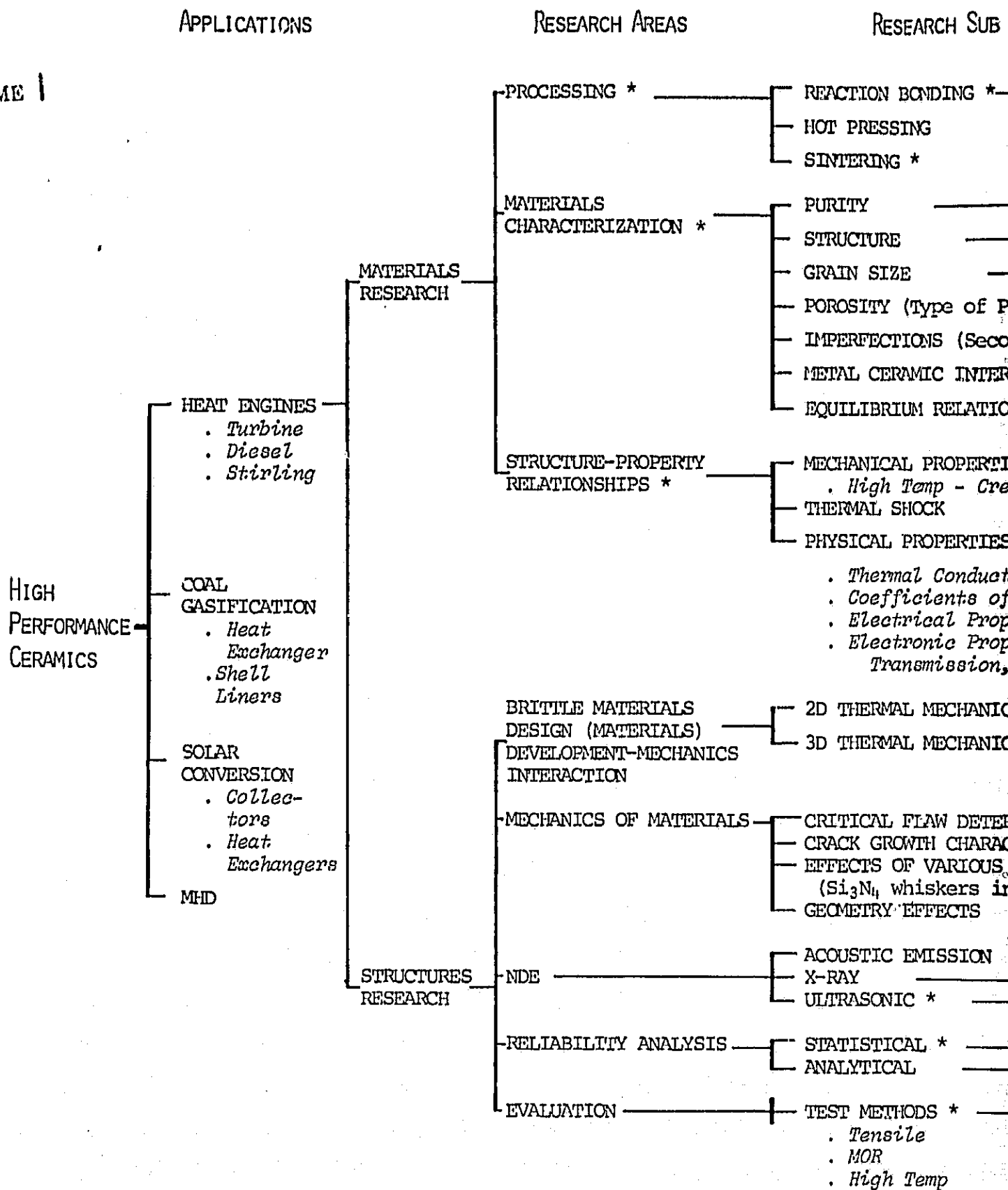
Organization

Emphasis at the present time is on the structures and related materials problems in a ceramic turbine engine.

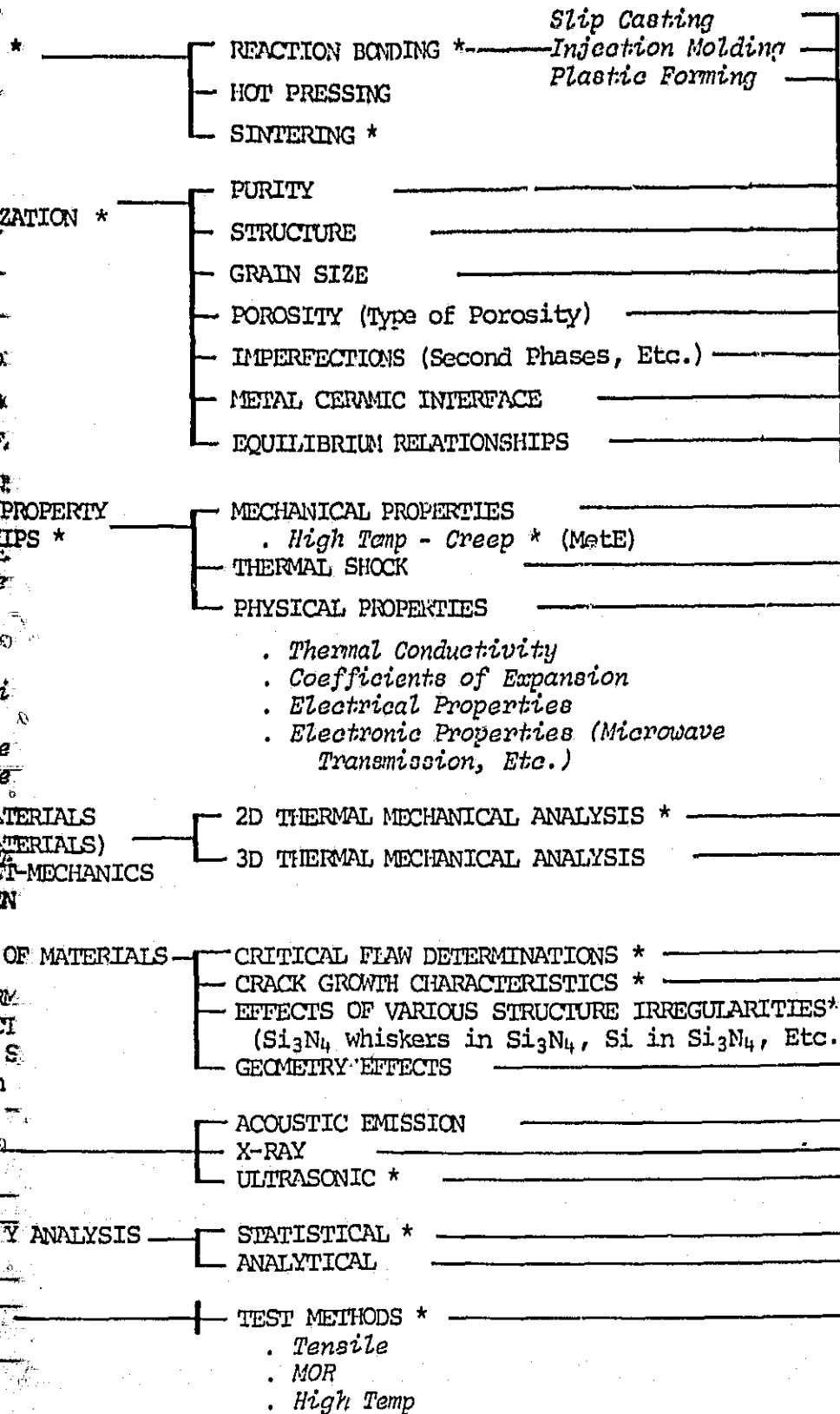
The research program has been established so that all departments in the University that may contribute to the program are aware of the goals of the program and they participate in defining the individual areas of research that are to be undertaken. Those departments now involved are physics, aeronautics and astronautics, mechanical engineering, electrical engineering, civil engineering and of course, metallurgy and ceramics.

The general planning of the program is carried out and coordinated by the ceramic engineering faculty. The overall research program is derived by the following type of analysis where a research emphasis is defined from what is going on around the world and establishing those things that need to be done to complete the attack on the problems, and to approach new areas of interest in new materials, processing, characterization, and non-destructive testing. We are using the chart on the following page to assist in defining the various areas of application.

FOLDOUT FRAME 1



RESEARCH PLAN
HIGH PERFORMANCE CERA



PROCESS OPTIMIZATION (Reaction Bonded Si_3N_4)
 . Grain Size Distribution * (Cer)
 . Pore Characteristics * (Cer)
 . Internal Surface Characterizations* (P)

PHYSICAL AND MECHANICAL PROPERTIES OF HIGH PURITY MATERIALS (Si_3N_4)

- . Structure Property Relations in Polycrystalline Si_3N_4 * (Cer)
- . Single Crystal Si_3N_4 * (Cer)
- . Properties of Whiskers - Si_3N_4 * (Cer)
- . Dislocation Studies - Single & Poly Si

PLASTIC FORMING

- . Sheet Rolling
- . Extrusion
- . Closed Die Forging

INJECTION MOLDING

- . Shape Possibilities
- Heat Exchangers
- Piston
- Pump Parts
- Space Vehicle Structures

MECHANICS-MATERIALS INTERACTION TO DESIGN AND FABRICATE

- . Shroud
- . Combuster
- . Nozzle
- . Diffuser
- . Turbine Rotor
- Axial
- Radial-Turbocharger
- . Stirling H
- . Missile No
- . Diesel Pis
- . Heat Exchan

NON DESTRUCTIVE EVALUATION

- . Ultrasonic * (EE)
- . Microwave

MECHANICAL TESTING

- . MOR Bar Evaluation * (AA, CE)
- . Crack growth phenomena * (ME, Cer)

* UW/CSM (Dept)
 PROGRAM

RESEARCH PLAN
 HIGH PERFORMANCE CERAMICS

ORIGINAL PAGE IS
 OF POOR QUALITY

MEASUREMENT OF CRACK VELOCITY IN CERAMICS

Faculty Supervisor: H. D. Scott, Professor
Ceramic Engineering

Graduate Assistants: Diane Martin, M.S. Student
Research Assistant

Kenneth Davido, M.S. Student
Research Assistant

Purpose:

To develop new instrumentation techniques to measure and record crack growth velocities in opaque ceramic materials using a calibrated electrical grid applied directly to the specimen.

Relevance:

a. Ceramic materials are subject to static fatigue or slow crack growth under stress. In some materials, e.g., glass, this occurs at room temperature in the presence of water vapor. In other materials, such as Si_3N_4 , it occurs at high temperature, probably by combined stress corrosion and plastic deformation mechanisms. Methods of predicting lifetimes of components in service, notably proof test techniques, require a detailed knowledge of crack growth behavior. The technique is to establish the size of the largest possible crack with a proof test and predict how long it will take this crack to grow to a critical size in the service stress. Thus, crack growth velocity data is essential.

b. Present techniques of obtaining crack growth data are tedious, require many specimens, and are open to some analytical criticism. The technique proposed here would provide a greater amount or more accurate information from a single specimen. It would enable researchers in materials development to evaluate rapidly new materials with regard to the important parameter of slow crack growth behavior.

Objectives:

The first year objective was to evaluate the feasibility of the technique at room temperature using microscope slides. We know from other workers the crack growth behavior of this material. We will be evaluating the following points:

- a. What is the relationship of the metal grid fracture to the underlying ceramic fracture? Does the metal grid fracture follow the ceramic fracture exactly?
- b. What level of electrical signals can be generated through the grid and how can these be measured and recorded?
- c. How reproducible, reliable, and applicable are the photo-lithographic techniques used to form the metal grid system?

The second year objective is to consider modifications necessary to obtain high temperature data, e.g., platinum plating, and to make measurements on DCB specimens.

The third year objective is to consider high temperature measurements on new specimen configurations: For example, the constant K specimen being developed as another part of this Structural Ceramics Program.

Progress

The first year objectives have been attained. Chrome metal grids 1 cm wide by 2 cm long with 1000, 10 μ m lines with 10 μ m intervals have been fabricated. Twenty five 2.5 x 9 cm slides have been measured in the Double Cantilever configuration, and crack velocities from 1.7×10^{-10} m/sec to 1×10^{-5} m/sec have been measured.

S.E.M. and optical microscope examination has established that a definite brittle severance of chromium lines occurs at the crack tip. Crack tips arrested in the grid and crack front profiles have also been photographed.

Grinding damage in the crack channel has been observed. This could influence the movement of the crack tip and affect velocity measurements. However, no quantitative evaluation of this effect has been attempted. Subsequent work involving HF etching and/or thermal annealing has been proposed as a method to reduce effects of slot damage.

The data obtained to date is being analyzed with respect to consistency within and between samples and in comparison with published literature values of crack velocity versus stress intensity factor. For the second year objectives of high temperature measurement, glass slides coated with tin-oxide have been obtained. These will be fabricated into grids and evaluated first at room temperature. Attempts will be made to minimize the influence of grinding damage at the root of the crack-grinding slot.

The use of high resistance tin-oxide grids is expected to improve the sensitivity of the measurement of crack velocities. If this is true, then a higher speed data acquisition system could be employed with the added possibility of accurately measuring crack velocities over a wide range of stress intensity factors in a single specimen. However, in terms of life time prediction, the lower velocities are of interest, and this technique has already proved its usefulness in measuring velocities in the range 10^{-9} m/sec where the fracture of one guide line (20 μ m advance) occurs in approximately 5.6 hours.

STATISTICAL DISTRIBUTION OF MODULUS OF RUPTURE RESULTS FOR CERAMIC MATERIALS

Faculty Supervisor:B. J. Hartz, Professor
Civil EngineeringGraduate Assistant:Tomio Hosokawa, M.S. Student
Research AssistantPurpose:

To study the influence of certain test variables on the statistical distribution of the modulus of rupture in ceramic materials and to evaluate the adequacy of the Weibull distribution at the low end of the probability distribution curve.

Relevance:

Both aspects of this project have extremely important practical applications since the modulus of rupture is the most widely used measure of mechanical properties of ceramic materials, and also, the most important part of the probability distribution curve is in the range of low probabilities of failure where the Weibull distribution, although widely used, does not accurately fit the observed test data in many cases.

Progress:

A special test fixture for rapid testing of a large number of readily available alumina substrates was built. A special strain indicator unit with a reading feature to preserve the peak load at failure of the specimens was obtained.

Several thousand specimens have been tested using 3-point and 4-point bending with two lengths of test specimens and with the notch on the substrate on both the tension side and the compression side. Probability distribution curves and Weibull distributions have been determined for each set of test conditions.

ORIGINAL PAGE IS
OF POOR QUALITY

EVALUATION OF TESTS FOR MECHANICAL PROPERTIES OF CERAMIC MATERIALS

Faculty Supervisor:

R. J. H. Bollard, Professor
Aeronautics and Astronautics
(On-leave 1977)

Purpose:

To aid in the critical review of current characterization testing and to design and improve uniaxial and multiaxial testing programs.

Relevance:

The significance placed upon the determination of modulus of rupture makes necessary a thorough understanding of the testing techniques and a complete analysis of the actual stress state existing in the test specimen in typical test configurations.

Progress:

The project supervisor has been on sabbatical leave during the report period and will initiate this project January 1, 1978.

FRACTURE TOUGHNESS DETERMINATION OF CERAMIC MATERIALS

Faculty Supervisor:

Ashley F. Emery, Professor
Mechanical Engineering

Albert S. Kobayashi, Professor
Mechanical Engineering

Graduate Assistant:

Leon I. Staley, M.S. Student
Research Assistant

Tusher Basu, Ph.D. Student
Research Assistant

Purpose:

The purpose of this exploratory investigation is to identify and possibly to provide solutions to critical fracture mechanics problems in ceramic structures. The long range objective of this research effort is to define the fracture mechanics requirements necessary to maintain the integrity of a ceramic structure in a hostile environment.

Relevance:

(a) Possible solutions to identifiable problems in fracture of ceramics could lead to design procedure which could reduce the fracture sensitivity of ceramic structures exposed to a hostile environment for a prolonged period of time.

(b) This basic research in fracture of ceramics will require extensive developmental work in predictive procedures for sustained stress crack growth and for statistical fracture strength and in the use of fracture mechanics to study erosion of ceramics.

Objectives:

(a) The first year objective was to identify critical areas where contributions to the state-of-art in the fracture of ceramics could be made. Development of a fracture specimen suitable for high temperature testing was identified as suitable area of investigation.

(b) The second year objective is to develop such fracture specimen. Simultaneously, an exploratory study for incorporating applied fracture mechanics to ceramic structural design will be initiated.

(c) The third year objectives, which will be guided by the progresses of the first and second years of research, are expected to be similar to those of the second year.

Progress:

(a) Accomplishments: Alumina 450 tapered DCB specimens, 0.25 inch thick, with notch radius less than 0.01 inch were precracked and fractured at room temperature. A minimum of 10 percent side grooving was found necessary to stabilize the crack path and reduce scatter in the fracture toughness. No detectable stable crack growth was observed in room temperature testing. A loading fixture for high temperature fracture testing of this alumina tapered DCB specimen was made and the vacuum furnace attached to the 30,000 lb Instron testing machine is being prepared for high temperature fracture testing.

(b) Problem Area: Sensitivity of the calculated stress intensity factor to the coefficient of friction between the loading pin and notch surface is a critical problem since this coefficient of friction cannot be measured with any certainty under the operating environment. Our present plan is to circumvent the problem by placing an oversize pin at the notch mouth to ensure an infinite coefficient of friction. Stress intensity factor for this new test configuration must be rederived now.

(c) Progress Towards Current Year Objectives: Upon completing the necessary repair and modifications to the vacuum furnace, the testing machine will be readied for high temperature fracture testing of alumina tapered DCB specimens.

(d) Degree Recipient: MS in ME awarded to Leon I. Staley.

(e) Paper Presented: A paper entitled "A Fracture Specimen For High Temperature Testing" by A. S. Kobayashi, L. I. Staley, A. F. Emery and W. J. Love was presented at the International Symposium on the Fracture Mechanics of Ceramics, Pennsylvania State University, July 27-29, 1977.

(f) Paper Published: The above paper will appear in the Conference Proceedings scheduled for publication summer 1978.

Correlative Research:

A. F. Emery, A. S. Kobayashi and W. J. Love are in their four-year research contract with EPRI concerning static three-dimensional fracture mechanics and dynamic fracture of pressurized pipes and pipe joints. The states of art in fracture mechanics and fracture dynamics advanced through this research effort are directly applicable to our research program in ceramic fracture. In addition, A. S. Kobayashi is in his thirteenth year of contract research with ONR involving dynamic fracture which again is directly applicable to our work in ceramic fracture.

A STUDY OF HIGH TEMPERATURE CREEP IN CERAMIC MATERIALS FOR STRUCTURAL APPLICATIONS

Faculty Supervisor:

Robert G. Stang, Assistant Professor
Metallurgical Engineering

Graduate Assistant:

David Hata, on leave from Fuels and Controls Section, Westinghouse-Hanford Company, Richland WA. Mr. Hata joined the program on October 1, 1977. His degree objective is an M.S. in Met. Eng.

Purpose:

The purpose of this segment of the CSM research program is to study high temperature deformation in hot pressed Si_3N_4 . The research is focusing on the contribution of grain boundary sliding (GBS) to the creep strain. This research program requires construction of a compression creep machine capable of testing materials at stresses up to 5.52×10^2 MPa (80,000 psi) and at temperatures up to 1450°C in air. This equipment is being designed so it could be used by other investigators to study materials which might be produced in the future. The experiments planned on hot pressed Si_3N_4 will serve two purposes; first the strain time data generated will be used to check the apparatus to make sure that the data produced is in agreement with that produced by other investigators working with the same material under similar conditions. In addition we plan to investigate the contribution of grain boundary sliding to the total creep process. GBS will be monitored by studying the offset, at the grain boundaries, of lines scribed on the polished surface of hot pressed Si_3N_4 . These results should lead to important conclusions concerning the importance of GBS on the rate controlling creep process as a function of stress and temperature.

Relevance:

The microscopic mechanisms which control high temperature plastic deformation must be determined to identify the best method for strengthening materials used in these applications. For materials used in creep applications this is often done by determining the stress and temperature dependencies. This data is used to formulate a model which describes the strain rate as a function of stress and temperature. The effects of impurity additions and microconstituents on the parameters in models of this type can be used to optimize and/or predict the deformation behavior of the material under study for different stress and temperature conditions.

Objectives:

First Year

1. Design of a compression creep machine capable of operating in air at temperature up to 1450°C and stresses up to 80,000 psi.
2. Selection of a suitable candidate material.

Second Year

1. Construction and testing of the creep apparatus described in (1) above.
2. Begin experimental program. This will involve collection of strain-time data as a function of stress and temperature.
3. Formation of model to describe strain-time behavior as a function of physical parameters.
4. In parallel with the strain-time description we plan to determine the effects of grain boundary sliding on the total deformation process.

Progress:

The conceptual design of a compression creep machine is complete. Procurement of the materials necessary to fabricate the components of the machine and construction of the apparatus is underway. A review of the literature has suggested that an interesting material to study would be one of the hot pressed silicon nitride products currently on the market such as NC 132, manufactured by The Norton Co. A block of this material has been obtained from AMARC by A. E. Gorum. A major problem area is the fabrication of suitable test samples from this material. Data available in the literature (1,2) suggests that creep deformation in this material occurs by grain boundary sliding under certain conditions of stress and temperature. Use of this material in our experimental program will allow us to compare data obtained from our apparatus with data published in the literature. In addition by scribing lines on the polished surfaces of undeformed samples, we can monitor the contribution of grain boundary sliding to the total creep strain by measuring the offsets in these lines at grain boundaries. This should provide a unique opportunity to check the theories based on grain boundary sliding with experiment.

1. R. Kossowsky, D.G. Miller and E.S. Diaz, Journal of Mat. Sci. 10 (1975) p. 983.
2. M.S. Seltzer, Cer. Bull. 56 (1977) p. 418.

Correlative Research Programs Supervised by R. G. Stang:

High-Temperature Low-Stress Creep of Copper 1% Al₂O₃ Composite Material, Myung-Shik Han, M.S. Candidate.

Orthopedic Internal Fixation, with Professors T.G. Stoebe and D.A. Spengler, M.D., S.M. Colella, M.S. Candidate.

An Investigation of the Effect of Stress Changes on the Subgrain Structure Developed During High Temperature Creep in High Purity Aluminum, Iris Ferreira, Ph.D. Candidate.

ORIGINAL PAGE IS
OF POOR QUALITY

RESEARCH ON HIGH PURITY MATERIALS (Si_3N_4 and Si C)

Faculty Supervisor: A. E. Gorum, Research Professor
Ceramic Engineering

Graduate Assistants: Charles Newquist, M.S. Student
Research Assistant

George Reini, M.S. Student
Research Assistant

Purpose:

The purpose of this part of the CSM program is

1. To learn how to make high purity Si_3N_4
2. To establish base line data (structure property relationships) for high purity Si_3N_4
3. To understand the role of additives, if they are really necessary, in various kinds of processing.

The program at present breaks down into specific areas.

A. Whisker growth and evaluation:

1. Preparation of large whiskers (single crystals)
0.5 mm by 2-3 cm have been reported.
2. Definition of mechanical properties.
3. Structure and orientation determinations (x-ray).
4. Dislocation studies by electron transmission and etching techniques.

B. Growth of whiskers on single crystal silicon to observe rates and growth habit.

C. Preparation and evaluation of high purity reaction bonded Si_3N_4 .

1. Nitriding of loose packed powders of high purity silicon.
 - a. Observe whisker structure formed. Estimate amount of volume that is whiskers.
 - b. Define by observation apparent bond strength of whiskers to grains.
2. Nitriding of fine grained compacts of pure silicon.
 - a. Observe progress by metallography as nitriding progresses.
 - b. Determine mechanical properties of high purity reaction bonded Si_3N_4 .
 - c. Determine amount and character of porosity as well as unreacted silicon.

- d. Postulate optimum grain size and distribution and make specimens to optimize structure and evaluate. This may well involve bi or tri modal distribution to optimize density as well as controlling the reaction bonding characteristics.

D. Sintering Studies - Si_3N_4 .

Very fine grained Si_3N_4 is now available from two sources. Work to date has all employed additives which degrade the properties. Investigation of methods to make a high purity material by this technique.

- E. Decomposition of inorganic polymers to produce high purity fine grained Si_3N_4 and Si C. Recently work has been initiated in two or three organizations (primary work has been in Japan). To produce fibers for composites. (Si C). We propose to go directly from the polymer by various processing techniques such as press forming, injection molding, and extrusion to a final shape. This technique has a great deal to offer in energy savings as compared to reaction bonding.

Relevance:

By understanding the behavior of high purity materials prepared by different techniques, it should then be possible to make materials that relate to specific applications whether it might be a heat exchanger tube or a turbine rotating part. It also allows trade offs as to properties, energy requirements for certain processes, etc.

Objectives:

The first year will see the equipment ready and all of the defined areas under way. One or two of the studies should be complete. The second year should be characterized by the completion of other areas of interest and initiation of new lines of interest depending on the results of the research and the way the general field of structural ceramics in the country is moving.

Progress:

A small high temp (1800°C) vacuum atmosphere furnace has been made ready for use and experimentation will begin in January 1978. A high temperature atmosphere testing furnace is under construction and will be available by the time testing is needed.

High purity silicon and Si_3N_4 have been obtained and are being characterized.

CHARACTERIZATION OF SILICON NITRIDE BY EXAFS

Faculty Supervisor:

E. A. Stern, Professor
Physics

S. M. Heald, Research Associate

Graduate Assistant:

H. Meuth, M.S. Student
Research Assistant

Purpose:

We propose to identify and characterize the surface properties of Si_3N_4 that are important to the sintering processes by which this material is produced. This will be done by the coordinated application of two different probes of the surface properties: adsorption isotherm and extended x-ray absorption fine structure (EXAFS) measurements. The isotherms will be used to identify the population distribution of different types of adsorption sites characterized by their differing adatom binding energies. The microscopic structure of these sites on an atomic scale can then be determined by the EXAFS measurements. Studies of samples produced under varying conditions should allow us to correlate the microscopic surface properties with sintering parameters.

Relevance:

At present detailed knowledge on an atomic scale of the microscopic physical processes involved in sintering is not available. The present work is aimed at developing such knowledge for one particular material, Si_3N_4 , but with the expectation that much of the same knowledge can be carried over to other materials. Once the physical basis of the sintering process is better understood, then this knowledge can be applied to optimizing the fabrication of technologically important products. In the case of Si_3N_4 , these include components exposed to high temperature environments such as high performance gas turbines and combustion chambers. In the past much of this optimization has been on a trial and error basis.

Objective:

The first year of this project will be devoted to construction and testing of necessary equipment, and the beginning of initial isotherm measurements. From the results of these initial measurements we will be able to refine our equipment and prepare for making EXAFS measurements. EXAFS measurements will begin during the second year which will be on the better characterized system of Kr on graphite in order to fully develop the use of adsorbed Kr as a surface probe. Also, initial EXAFS measurements will begin on Si_3N_4 at this time, which will continue in earnest during the third year. Any further isotherm measurements suggested by the EXAFS results will also be made during the third year.

ORIGINAL PAGE IS
OF POOR QUALITY

Progress:

During this initial 6 month period most of the equipment necessary for the isotherm work has been assembled and tested. We have gained important experience in the acquisition and analysis of EXAFS data from adsorbed systems through our continuing studies of Br₂ adsorbed on graphite. So far no unusual problems have appeared, and we should be able to meet the first year goals outlined above.

DETERMINATION OF SURFACE PROPERTIES BY PHYSISORPTION

Faculty Supervisors:

J. G. Dash, Professor
Physics

O. E. Vilches, Associate Professor
Physics

Graduate Assistant:

Manu Tejwani, Ph.D. Student
Research Assistant

Purpose:

The purpose of this project is to apply refined physisorption measurements to the study of the surface properties of ceramic powders and compacts.

Relevance:

The application of knowledge of the surface characteristics of ceramic powders to ceramic processing should lead to more effective production of many polycrystalline materials currently of interest to many private and federal programs.

Objectives:

As stated in previous reports, the long range objective of this program was to investigate the effect of surface preparation on the initial stages of sintering. Through previous research at our laboratory and at other places, a fairly detailed knowledge of the correlation between surface preparation and adsorption isotherms of Kr at liquid nitrogen temperature is available. Our program intended to use this knowledge to a) prepare MgO powder with a well characterized surface, and b) use this powder in compaction and sintering studies.

Progress:

We prepared our own MgO powder samples by burning Mg ribbon in static air inside a bell jar, then collecting the powder by electrostatic precipitation. The powder showed, by electron microscopy, almost 100% cubes of typical linear dimensions 0.1 μ m. The specific surface was 7 m²/gm, the reduction of area from a geometric calculation being due to few large size particles. In spite of the high quality of the prepared powder, Kr adsorption isotherms showed more of the features characteristic of adsorption on uniform surfaces. A systematic study of the changes in the features of the adsorption isotherms as a function of heat treatment of the samples was initiated and showed that a minimum of 700°C was needed to produce steps in those isotherms. A 900°C heat treatment produces enough steps and features to show layer by layer completion and vertical risers characterization of 2-phase surface phases coexisting at that density and temperature.

Techniques for compacting the powder were then investigated. Slurries of MgO smoke and methanol and N-propyl alcohol were prepared. A compaction to about 30% of bulk crystal density was obtained. Heat treatment to 900°C gave again isotherms similar to the uniform substrate.

Compaction by making slurries with water were also tried. The compacted sample of $\text{Mg}(\text{OH})_2$ was then heat treated. With heat treatment temperatures up to 500°C the isotherms showed no features. Higher temperature treatment decomposed the $\text{Mg}(\text{OH})_2$ into a much smaller particle size MgO of very high uniformity as revealed by the isotherms. The area of this MgO powder is about $24 \text{ m}^2/\text{gm}$.

An article describing our findings and possible explanations for the surface changes occurring during heat treatment was prepared and submitted recently to the Journal of Physical Chemistry. In addition, samples of MgO smoke have been prepared for studies of light scattering at MIT, neutron scattering by adsorbed films by a UCLA group, and nmr of adsorbed ^3He at Wesleyan University. We have prepared a highly compacted MgO sample by the water compacting method that we intend to use for a calorimetric study of Kr adsorbed on MgO to identify the character of the surface phases revealed by the isotherm work.

We are designing a new isotherm apparatus for pursuing the MgO work towards the original goal of detecting changes brought about by sintering.

OPTO-ACOUSTICAL TECHNIQUE FOR LOCATING DEFECTS IN CERAMICS

Faculty Supervisor:

John L. Bjorkstam, Professor
Electrical Engineering

Graduate Assistants:

Michael Morgan, M.S. Student
Research Assistant

Purpose:

The purpose of this research is to evaluate the potential of an opto-acoustic technique for use in the detection of internal (as well as surface) flaws in ceramics. The use of ultrasonic imaging and scattering methods is a maturing discipline which has already found many applications in non-destructive-evaluation (NDE), biomedical engineering, etc. Our work addresses the special problem of detecting internal flaws in materials with high acoustical attenuation.

Relevance:

(a) In ceramic components, flaws at which failure initiates may be as small as ~ 5 times the mean grain size. To realize appreciable acoustical scattering from a flaw, and thereby detect its presence before failure occurs, it is necessary for the wavelength of the scattered energy to be comparable to, or smaller than, the flaw size. As a typical example the flaw size may be $\sim 25 \mu\text{m}$ in diameter, with normal mean grain sizes in the $1\text{--}5 \mu\text{m}$ range. With sound velocities $5 \times 10^5 \text{ cm/sec}$, if the wavelength is to be $\leq 25 \mu\text{m}$, frequencies must be $\geq 200 \text{ MHz}$. In this frequency range piezoelectric transducers are incapable of generating sufficient acoustical power to allow detection after passage through a necessary thickness of most ceramic materials. Acoustical pulses generated by differential thermal expansion due to high-power laser pulses absorbed at the ceramic specimen surface are expected to have peak pressures from 10^2 to 10^4 greater than can be realized with piezoelectric transducers. Such pulses could traverse correspondingly greater thicknesses of ceramics with a detectable scattering of energy from internal flaws. By also using optical techniques for detecting the scattered acoustical wave the necessity to sputter on piezoelectric transducers is avoided. We thus believe that such a system should have important applications in production NDE formats.

(b) The opto-acoustic methods for generation of high-energy acoustical pulses, as well as the optical detection and signal processing aspects of the scattered acoustical energy, fall naturally under the purview of modern electrical engineering. This project allows us to bring-to-bear our expertise on a materials problem of interest in other disciplines. In so doing we have opportunity to be exposed to new problems, and the need to learn about other than electromagnetic properties of materials.

Objectives:

Our first year objective has been to identify the major problems which must be overcome to optimize the generation and detection of the shortest possible acoustical pulses, given the availability of laser pulse trains with optical pulses in the pico second range. Any system which we design and build must of course, have the necessary sensitivity and convenience to allow flaw detection in technologically useful ceramic components. During the first year we expect to demonstrate pulse generation and detection in solids. During the second year we expect to refine the system and demonstrate that the method may be applied to production ceramic parts. If these studies demonstrate utility of the method, further refinements will be incorporated.

Progress:

Mr. Michael Morgan, the first student to be supported on this project, began in August. He has been giving attention to the mechanism of the acoustical pulse generation at the ceramic surface: What limits the minimum pulse length which can be generated? What should be the optical absorption characteristics of the surface, or a material in contact with the surface? What, if any, material properties will limit the maximum pulse intensity which can be generated? In addition the questions of format for an optical probe to detect surface excursions due to scattered energy in the ceramic sample have been addressed. What system will give the necessary sensitivity with respect to expected surface excursions? What must be the necessary bandwidth to allow information on flaw-size to be extracted from the scattered beam? The calculations to date lead us to be quite optimistic as to the capabilities of such a system. We will soon be in the design mode of a specific system which utilizes a portion of the energy in the pico second train of optical pulses, available from the laser at our disposal, to gate a second helium-neon laser which will probe the ceramic surface excursions. This probing laser will be used in conjunction with a so-called "knife-edge" technique developed in other laboratories measuring changes in surface slope due to incidence of a scattered acoustical pulse.

In spite of the somewhat late date of which Mr. Morgan began work on the project we believe we are approximately on schedule with respect to our first year objectives.

INTERDISCIPLINARY RESEARCH PROGRAM

Prior to the last year, the major thrust of the NASA-funded effort at this institution was towards interdisciplinary research on the nature and properties of ceramic materials. The program, in recent years, had been divided into three major research areas - solid electrolytes, ceramic fibers, and processing. Reorientation in 1976 necessitated non-renewal of funds for these projects except for those manned by students to whom support commitments had been made. The projects supervised by Professors Dash and Stern were originally in this category but both are redirecting their efforts to conform to the new program. Some residue of their previous work may have been noted in their reports. The following covers the remaining research in this category.

ORIGINAL PAGE IS
OF POOR QUALITY

GRAIN BOUNDARY EFFECTS IN BETA-ALUMINA

Faculty Supervisor:

Alan D. Miller, Associate Professor
Ceramic Engineering

Graduate Assistant:

Douglas O. Powell, Ph.D. Candidate
Research Assistant

Purpose:

The purpose of this project is to improve the understanding of the role of grain boundaries in the conduction process in fast ionic conductors, particularly in beta-alumina. The effects of grain boundaries will be studied with respect to their purity, orientation and extent.

Relevance:

Since the application of solid electrolytes will almost certainly involve polycrystals rather than single crystals, it is important to understand the degree of influence of grain boundaries upon the conduction process. Any contribution as to the nature of the conduction process will help to provide a predictive capability in the development of improved systems. If the results can be generalized to describe the importance of boundary processes in low-activation energy electrolytes, a further predictive capability will be realized. This work, which utilizes a.c. conductivity measurements as an experimental tool, is complementary to the tracer diffusion studies on polycrystalline beta-alumina done under Professor Sarian's supervision.

Objectives:

Objectives for 1978 are:

1. To evaluate the a.c. conduction behavior of oriented polycrystalline specimens by comparison with the behavior of equivalent circuit models of possible processes occurring in the specimen.
2. To verify the applicability of chosen equivalent circuit models by varying sample geometry and by conducting four-probe measurements.
3. To correlate the results of the a.c. conduction experiments with results from tracer diffusion experiments on polycrystalline specimens.
4. To develop a physical model of the grain boundary region in beta-alumina which will improve our ability to predict microstructural effects upon d.c. conductivity.

Progress:

The new test system mentioned in the two previous reports has been completed, tested and calibrated. 20 samples with varying microstructure have been fabricated and characterized in preparation for testing. Work over the next several months will consist of data collection and reduction.

CARBON MATERIALS RESEARCH

Faculty Supervisor:

David B. Fischbach, Research Professor,
Ceramic Engineering

Graduate Assistants:

Seshadri Srinivasagopalan, Ph.D. Student
Research Assistant (Army Research Grant)

Kunio Komaki, Ph.D. Student
Research Assistant (Army Research Grant)

George Mellinger, M.S. Student

Purpose:

To investigate the dynamic and static stress-induced behavior of carbon fibers and its relationship to structure and processing history. To investigate the structural characterization and the nature of thermally-induced structural evolution in carbons of various types.

Relevance:

Synthetic carbons are produced and used in a variety of forms which differ widely in structural morphology but have one thing in common: Structures are very disordered in the carbonized product and develop toward the equilibrium crystalline graphite structure with high temperature processing. Properties are very sensitive to microstructure which is dependent on both precursor and processing. Raman spectroscopy (inelastic scattering of optical photons by lattice phonons) is being investigated as a promising new structural characterization technique and probe into the nature of the structural imperfection within the layers which is difficult to investigate by more common methods such as x-ray diffraction. A better understanding of how structure and properties develop with thermal treatment is being sought thru studies on the graphitization process using various strongly structure-dependent properties (diamagnetic susceptibility and density as well as Raman spectroscopy) in combination with micrography and x-ray diffraction. Primary emphasis in these studies has been placed on difficult-to-graphitize carbons (e.g. glassy carbons, fibers) in which structural disorder is stabilized by the microstructural morphology. Carbon fibers are receiving particular attention because of their importance for structural applications, and because they are derived from several precursor categories. The dynamic modulus and damping characteristics and the piezoresistance behavior of carbon fibers are being investigated under support of an Army Research Office grant to gain new insights into the relationship of mechanical properties in microstructure. The role of fibrillar ("stranded cable") substructures in the micromechanical behavior is of particular interest in these studies. These programs on characterization, graphitization and properties by various techniques complement each other.

Objectives:

1. To complete the analysis, interpretation and publication of NASA-sponsored research on the structure, properties and characterization of carbon materials and to terminate these projects.
2. To obtain a better fundamental understanding of the micromechanical characteristics of carbon fibers from various precursor types thru investigation of dynamic torsional characteristics and piezoresistance behavior.

Progress:

During this period, three papers were presented at the 13th Biennial Carbon Conference and published as conference extended abstracts. An undergraduate research project on carbon fiber graphitization was completed and further data were obtained on the diamagnetic characterization of fibers, particularly those from pitch mesophase. Construction of apparatuses to study the temperature dependence of the dynamic torsional behavior and the piezoresistance of fibers was begun. Work continued on the analysis, interpretation and write-up of results on the graphitization behavior of glassy and fiber carbons and the Raman spectroscopy of various carbon materials.

Raman spectra are being analyzed quantitatively in terms of the ratio R of the intensity of the 1360 cm^{-1} disorder line to the intensity of the 1580 cm^{-1} graphite line. As reported earlier, there are characteristic differences in plots of R vs tensile modulus for fibers from different precursors. With increasing E , R decreases monotonically, but along different paths, for fibers from pitch, rayon and pitch mesophase; however, the plot for fibers from PAN was unusual, showing a sharp peak at $E = 250\text{ GN/m}^2$. Recent analysis of data on PAN fibers heat treated in the range $1200\text{--}2000^\circ\text{C}$ indicates that this peak is probably an artifact resulting from difficulties in determining R for the lowest modulus fibers. These new results show that R is large in as-carbonized fibers but drops sharply in the $1200\text{--}1800^\circ\text{C}$ treatment ranges in which residual nitrogen is evolved. The error in the earlier analysis resulted from the exceptionally large breadth and overlap of the lines in carbonized PAN which makes R determination difficult. Work continues on the analysis and write-up of Raman results on other carbon materials.

The fiber piezoresistance studies at room temperature have been troubled by small, apparently irregular changes in the measured resistance. Now it has been found that curing of the silver paint contacts can cause detectable decreases in resistance; and that water adsorption significantly increases the resistance of as-carbonized fibers from rayon; but the major source of difficulty is the large negative temperature coefficient of resistance (TCR) of the fibers combined with poor laboratory temperature stability. Measurements of the TCR of rayon-based fibers in the $0\text{--}30^\circ\text{C}$ range have shown that it is high ($\sim 1300\text{ ppm}/^\circ\text{C}$) for as carbonized low-modulus fibers, drops to about 400 for graphitized low-modulus fibers, and increases regularly with modulus in hot stretched fibers, reaching ~ 1500 at 700 GN/m^2 (100 Mpsi). The resistance ratio (4.2 or $77/300\text{ K}$) of fibers from PAN and pitch mesophase has also been reported in the literature to pass thru a minimum with increasing heat treatment temperature and modulus. Careful room temperature ($22\text{--}24^\circ\text{C}$) measurements here on a medium-modulus fiber from PAN (Union Carbide T-300) showed that tensile

strain, which causes a positive piezoresistance, results in a small residual decrease in resistance and an increase in TCR on unloading. It is not clear whether the primary source of the TCR is in the band structure (variation of carrier concentration or mobility) or the microstructure (variable series/parallel contacts between fibrillar substructure units) or both; but it is now evident that the TCR is a sensitive investigative parameter. Apparatus is being built to determine piezoresistance behavior under closely controlled but adjustable temperature conditions.

SEM observations have been made of transverse fracture surfaces of some Union Carbide pitch mesophase fibers ($E=26.7, 38$ and 52.9 Mpsi) both as-received and after heat treatment to $\approx 3000^\circ\text{C}$. Cross sections are circular and generally $9-11\ \mu\text{m}$ in diameter but some fibers are twice that large with hollow cores. The fracture surfaces are rough and the microstructures are laminar, graphitic and coarsely fibrillar. The basic substructure unit resolvable in the SEM consists of irregularly crinkled or curved layer packets $\approx 0.1\ \mu\text{m}$ thick and $\approx 0.5\ \mu\text{m}$ wide running parallel to the fiber axis. Layer orientation textures in the cross section are complex, and simple classification as random radial or circumferential (as reported in the literature) is not possible. In general, the texture near the periphery is predominantly radial, but the interior texture consists of multicentered lobed, circular and spiral patterns ranging in extent from $\approx 0.5\ \mu\text{m}$ to $\approx 5\ \mu\text{m}$. These structural features, combined with our observations that the torsional and piezoresistance properties of these fibers are similar to those of fibers from rayon and PAN, suggest that fibrillar micromechanical behavior is a general characteristic of carbon fibers and insensitive to fibril size.

During the coming period, we plan to obtain data on the controlled temperature piezoresistance behavior of carbon fibers; begin studies on the temperature dependence of the dynamic torsional characteristics of fibers; and complete final drafts of papers on Raman spectroscopy, dynamic torsional characteristics of pitch mesophase fibers, diamagnetism of carbon fibers and graphitization of glassy carbon.

Theses completed:

"Graphitization of carbon fibers," Douglas W. Gilbert, Senior Thesis, June 1977

Papers:

"Oxidation behavior of some carbon/carbon composites," D. B. Fischbach and D. R. Uptegrove, Extended Abstracts and Program, 13th Biennial Conf. on Carbon (American Carbon Society/Aerospace Corp./TRW, Inc. co-sponsors), University of California, Irvine, 18-22 July 1977, pp 130-1.

"Raman Spectra and Characterization of Carbon Materials," R. Vidano and D. B. Fischbach, *ibid.* pp 272-3

"Piezoresistance of Carbon Fibers," D. B. Fischbach and K. Komaki, *ibid.* p 298

APPENDIX I

COMMENTS FROM CRITIQUE OF SUMMER COURSE

Student A (ME) - If this is supposed to be a one-quarter course, I think it's a little much, especially for undergraduate students. As an ME student I would like to see more time spent on discussion of materials-testing and other aspects, including processing and phase diagrams. By all means we should spend more time in the laboratory.

Student B (Cer E) - I suggest that Professor Taggart start in the first session with design in order to emphasize what we are trying to do and why - that we are studying the design of turbine components and evaluating the effect of materials properties on the design. His discussions can be used as a guide line or the thread that explains why all the other subjects are important.

It was very helpful to have all the faculty present as that stimulated a lot of questions which resulted in discussions. I've found out that discussions are necessary in good design work. I think the most valuable session was the one where we were doing the MOR and the faculty and students were impersonally discussing what was taking place and asking questions of each other. When a class is too structured, this is lost.

Student A - I think it's necessary to get an exposure to stress analysis early in the quarter - you have to understand the basics in order to apply them in a numerical solution. I agree with the idea of starting with the design introduction but I think more time should be spent on why ceramics are being utilized.

Student C (Cer E) - This has been my first exposure to things like the continuum theory and I found them very interesting and I'd like to go a little deeper to obtain a better understanding. This is the first and only course of this nature I've had and it's my first exposure as a Cer. E. student, therefore I don't feel I've got the necessary background to cope with it. All in all I thought it was a very valuable experience for the students. We've been exposed to a fantastic amount of background material from which we can draw in the future.

Student D (CE) - This was a good effort but it was too fast. It was a good idea to have all the instructors present so they can eliminate some of the overlap in the future. It also seemed disconnected at times - I could not see where we were going.

Student E (CE) - I feel we were given the major problems and we had something of a short course on the properties of ceramic materials involved in designing with ceramic materials. If there are going to be undergraduates involved, it should be spread over two quarters. I agree there should be more laboratories in this program.

Student B - I enjoyed the class and learned something. I was more like a seminar than a structured classroom. The matter of continuity is important so it doesn't appear to be a series of disjointed topics throughout the course.

Student A - It would help to establish a motivation - "Why do we want to design with ceramic materials? - what are their advantages?" This could be a unifying theme which would make for greater coherence throughout the course. It is also a good idea to get the people involved early as it stimulates their interest in the course.

Student C - I agree that a main theme is needed to carry through the course. We have had a series of pigeon holes. It might be possible to show how some of the theoretical material can be made to apply to a simple application, like a MOR bar.

Mueller - You've been through this course, do you feel the original purpose of this course has been accomplished?

Student A - It was obvious to me you were trying to develop some interdisciplinary understanding - to be able to have interplay and to converse with each other in a meaningful way before we get out of school. That's how I see the goals and I guess we had some success.

Student C - It's pretty easy to go through an undergraduate education and not get the outlook of what other engineers do. I got a feeling this summer about how these things really work. I'm thrilled with all I've been exposed to but there's been no time to digest it. It really becomes frustrating.

Faculty A - We must make it clear this is not a course in the design of a gas turbine engine - that it is being used as an example - that there are many other places where design with brittle materials will apply.

Student B - As far as I am concerned it asked all the questions - it had all the elements of the concepts that had to be developed. You must have something to relate to. I think it would be better if we started with this and take up the basics as we used them in the design.

Mueller - We should write a scenario around the basic design, bringing in the stress calculations, then the materials, etc.

Student C - It would provide a foundation where you can see how all those other theories fall into place. I can't think of a better way to go about it.

Faculty B - We're going to have to get a more coordinated effort. We should present the material in such a way as to minimize the copying of the detailed mathematics and spend more time on the application of principles. We have to do the best we can but not lose sight of the student's needs to explore a little deeper.

Faculty A - It's been said that we only have ears for that to which our experience has given us an access. I think we've given these students an access here. They've been exposed to things to which they may have need in the next ten years and the material we've covered is still going to be valid in ten years, they'll keep recurring over and over again. If a student has not had some exposure then this has been a start and by using a theme, we've given them a start.

Faculty C - I really enjoyed the team-teaching approach we've used. It's been mentioned several times that we need more quiz period and laboratories and I think we should all cut back on our presentation material so the scheduled quiz and lab periods can be used as such, not as additional lecture time.

Faculty D - I think it was a good course even though I felt I was out in left field for a lot of it. I think we all learned something.

Faculty E - It was somewhat disjointed because we all worked independently in preparing our material. The second iteration should be the result not only of this discussion but the result of interaction by the faculty group. The problem is that within the time frame available in a University, we don't always have the time to interact.

Student B - I think you have the framework of an outstanding course. As far as I'm concerned, we are not required to think in most of the undergraduate and graduate courses. I've not had any courses which are set up to get people from different disciplines to really work together. Here you have a course which is really engineering and you'll turn out engineers. We've probably learned more than we appreciate and that appreciation may come later. I think you've made a fantastic start and I hope that what we said won't discourage you in any way. This is what engineering education should be.

Student C - I'm amazed that you've been able to accomplish this in such a short time. I'm really impressed with the fact that you've reached a way out goal. I think this discussion has helped too -- it helped me put a lot into perspective - it cleared up some of my concerns that really had me worried before we started this discussion. Things look a lot brighter now.

APPENDIX II

Papers Published:

D. B. Fischbach and D. R. Uptegrove, "Extended Abstracts and Program, Proceedings of the 13th Biennial Conference on Carbon (American Carbon Society / Aerospace Corp, / TRW., Inc. co-sponsors), University of California, Irvine, 18-22 July 1977, pp 130-1.

R. Vidano and D. B. Fischbach, "Raman Spectra and Characterization of Carbon Materials", *ibid.* pp 272-3

D. B. Fischbach and K. Komaki, "Piezoresistance of Carbon Fibers", *ibid.* p. 298

D. B. Fischbach & M. E. Rorabaugh, "Glassy carbon graphitization: Density change," High Temperatures/High Pressures, (to be published)

R. Vidano & D. B. Fischbach, "New lines in the Raman spectra of carbons and graphite," Journal of the American Ceramic Society, to be published in the November/December 1977 issue.

Papers Presented:

A. S. Kobayashi, "A Fracture Specimen for High Temperature Testing," presented at the International Symposium on Fracture Mechanics of Ceramics, Pennsylvania State University, July 27-29, 1977.

Degree Recipients:

Leon I. Staley, "Design and Preliminary Developmental Testing of a Fracture Specimen Suitable for Elevated Temperature Testing," University of Washington, M.S. in M.E., December 1977.